INTERFACE BY DESIGN FOR JOINING OF DISSIMILAR MATERIALS

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OVERVIEW

Timeline

- State date:
 - October 1, 2017
- End date:
 - September 30, 2020
- ▶ 40% complete

Budget

- Total project funding
 - DOE share: \$2,100K
 - Contractor share: \$0
- Funding for FY 2018: \$1,050K
- ► Funding for FY 2019: \$1,050K
 - \$650K/year at ORNL
 - \$400K/year at PNNL

Barriers

- Lack of reliable joining methods for dissimilar materials
- Lack of fundamental understandings on the bond formation mechanisms at the interface

Partners

- ORNL/PNNL/ANL
- Industry collaborations through materials supply and technical advisory committee

RELEVANCE AND IMPACT

- Technology gaps for lightweight metal body structures
 - Lack of proven technology for joining dissimilar metals (Steel-Al, Steel-Mg, Mg-Al, etc.)
 - The need to maintain the microstructure makes the use of conventional joining techniques nearly impossible.
 - Joining of thin sheet of AHSS is unreliable and fracture behavior is not understood.
- Technology Gaps-Composite Body Structures
 - Lack of dependable joining technology for the integration of composite components into the body structure



TECHNICAL APPROACH -- INTERFACE-BY-DESIGN

- Turning the equation around with validated computational models:
 - Key parameters determining the load-carrying capacity of a joint:
 - Effective bonded area, intrinsic bond strength
 - Inverse computational approach to quantify the key parameters for targeted joint load-carrying capacity:
 - Desired effective bonded area (including morphology) and bond interfacial strength
 - Perform process simulations (validated by experiments) to identify the joining methods and process parameters to achieve
 - Desired interfacial pressure, temperature history
 - Desired interfacial morphology
 - Perform massively paralleled molecular dynamics simulations validated by high resolution experiments to identify the associated interfacial characteristics needed in achieving the identified bond interfacial strength with:
 - Thermodynamics (chemistry driven) and kinetics (processing driven)
 - Diffusion and phase transformation

MILESTONES, PROGRESS AND ACCOMPLISHMENTS -- FOCUSING ON MG-STEEL INTERFACE

FY19 Milestones

- ORNL -- Demonstrate the interfacial by design framework in producing structural joints of Mg to bare High Strength Steel
- PNNL -- Predict and advise on optimum Mg-Steel interfacial design to maximize strength and ductility using FSS to produce a lap joint

FY19 Progress and Accomplishments

ORNL:

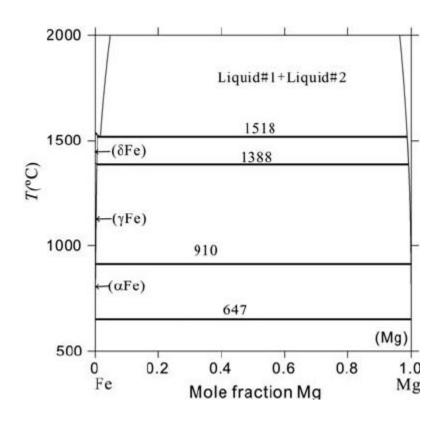
- Developed and validated forward prediction framework for Mg-steel interface with impact welding
- Demonstrated the validity of the interface by design framework with ultrasonic welding (inverse mapping)

PNNL:

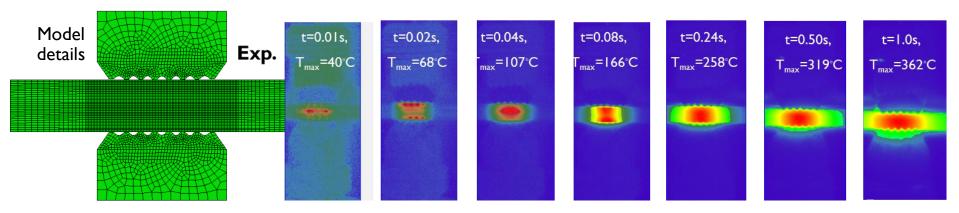
- Developed a framework for joint performance prediction of friction stir-based Mg-Steel joints
- Developed a combined modeling and experimental approach to mechanically characterize the interface obtained in the friction stir-based processes

FOCUS -- DEMONSTRATE THE INTERFACE-BY-DESIGN FRAMEWORK ON MG/STEEL INTERFACE

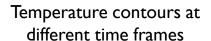
- FY18-19 focus: Develop and demonstrate Interface-by-Design by creating the metallurgical bond between Mg and steel (without coating)
 - High thermal physical property disparities
 - Mg/steel is an immiscible system
 - No intermetallic formation
 - Most solid state welding process claims the benefit of Zn coating
 - Mg/steel (bare) generally considered non-weldable

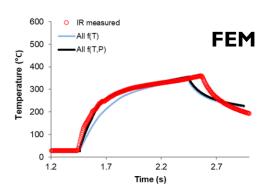


FY 18 ACCOMPLISHMENTS ON MG/MG INTERFACE -- VALIDATED PROCESS SIMULATION LINKING PROCESSINTERFACIAL TEMPERATURE FOR UW (ORNL)

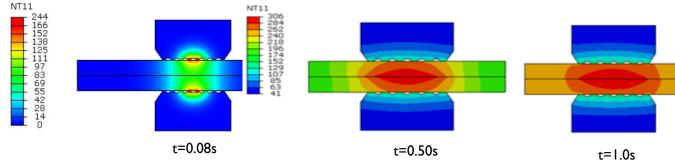


Minimum element size 100 μm x 100 μm



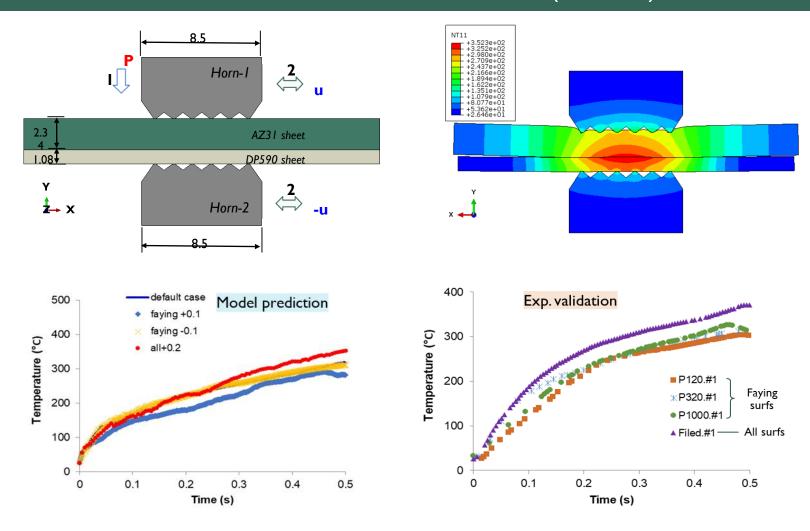


Dual sonotrode, Power=1000W, Frequency=20kHZ, Weld time=1 sec



Huang, et al., Simulation of heat generation in magnesium alloy AZ31 ultrasonic welding by a validated thermal-mechanical model, revision submitted to *Journal of Materials Processing Technology*, 2019.

FY19 ACCOMPLISHMENTS ON AZ31-DP590 INTERFACE -- VALIDATED PROCESS SIMULATION LINKING PROCESS-INTERFACIAL TEMPERATURE FOR UW (ORNL)



FY 19 ACCOMPLISHMENTS ON AZ31-DP590 INTERFACE -- VALIDATED FORWARD PREDICTION FRAMEWORK FOR MGSTEEL INTERFACE WITH IMPACT WELDING (ORNL)

Characterization

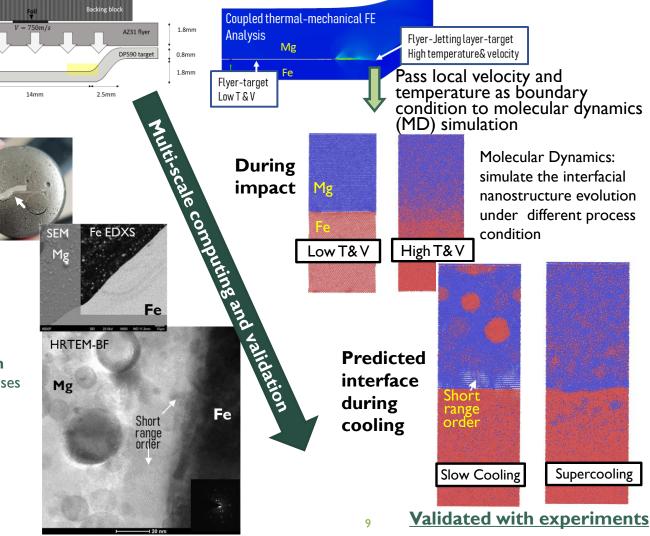
- I). Mg-Fe bond at lower corner
- 2). No Al- or Zn- intermetallic layer
- 3). Abundant Fe particles in Mg matrix
- 4). Short range orders at interface

Simulation

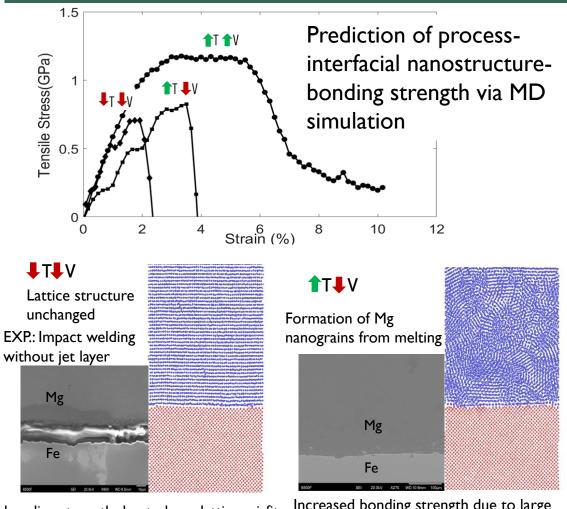
- FE: Jetting creates a high shear velocity high temperature intermediate layer at lower corner
- 2). MD: Predicts various nanostructure formation under different processing

Interfacial bond formation mechanism

- The high shear velocity at interface causes a "mechanical mixing" of Fe atoms into Mg.
- During cooling, Fe segregates into particles and forms short-range orders (SRO) at interface, which reduce misfit energy and leads to bonding.

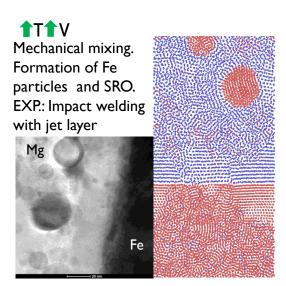


FY 19 ACCOMPLISHMENTS ON AZ31-DP590 INTERFACE -- VALIDATED FORWARD PREDICTION FRAMEWORK FOR MGSTEEL INTERFACE WITH IMPACT WELDING (ORNL)



Low bonding strength due to large lattice misfit.

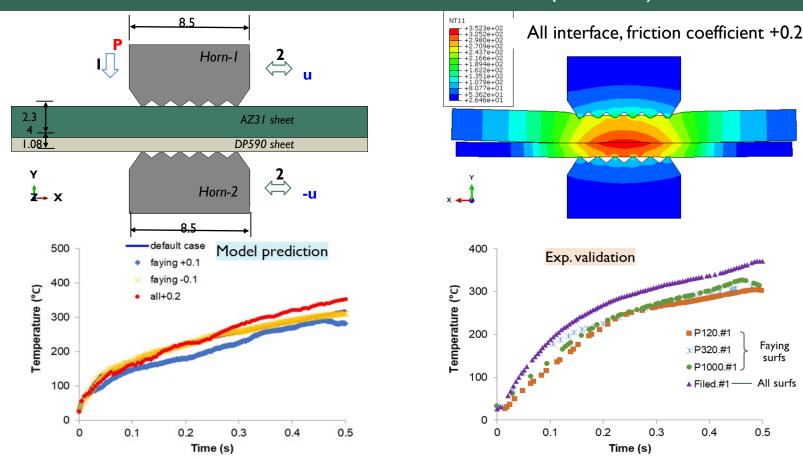
Increased bonding strength due to large grain boundary areas relax interfacial energy



High bonding strength due to SROinduced low misfit strain energy at interface

Guidance to process development
-- Can we modify the (ultrasonic)
welding process to locally increase
the temperature and lateral
velocity at Mg-Fe surface to obtain
a higher bonding strength Mg-Fe
interface?

FY19 ACCOMPLISHMENTS ON AZ31-DP590 INTERFACE -- PROCESS SIMULATION LINKING PROCESS PARAMETER-INTERFACIAL TEMPERATURE FOR UW (ORNL)



- Increased welding amplitude: increasing lateral velocity
- Increased welding time: increasing temperature

- Can heat generation be enhanced by surface engineering:
 - All surfaces roughened have highest temperature predicted by process model

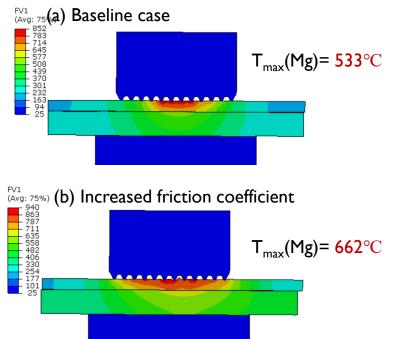
Faying

surfs

— All surfs

0.5

FY 19 ACCOMPLISHMENTS ON AZ3 I-DP590 INTERFACE -- EXPERIMENTAL VALIDATION ON STRUCTURAL BOND CREATION AND IMPROVEMENT WITH UW (ORNL)



No surface engineering

With surface engineering:
All surfaces filed

No surface and the surfa

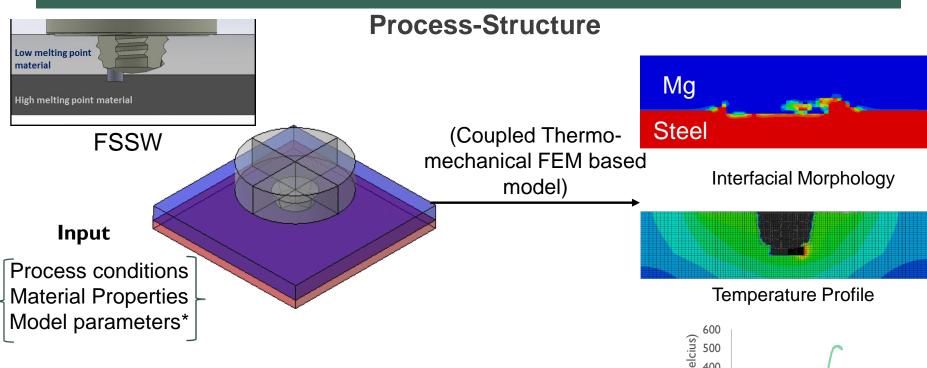
Predicted temperature distribution at 2.4s in Sonotrodeanvil welding setup

Achieved higher temperature for filed samples, which leads to increased bond area and bond strength

Comparison of joint strength between different welding and surface conditions

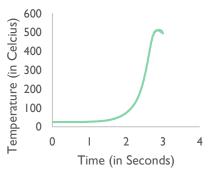
Surfs condition Case	Faying surface	Other surfaces	Welding Power and time	Condition	Tensile load
0	Sanded P80 (Mg)	As received	2500 W, 2 s	Baseline	Fail drop test
1	Sanded P80 (Mg)	As received	3500 W, 2 s	Increased velocity	Pass drop test
2	Sanded P80 (Mg)	As received	3500 W, 4 s	Increased welding time	3.9±0.5 kN
3	Filed	Filed	3500 W, 4 s	Surface modification	4.2±0.4kN

FY 18 ACCOMPLISHMENTS ON MG/STEEL INTERFACE -- PROCESS-STRUCTURE LINKAGE IN FRICTION STIR SCRIBE WELDING (PNNL)



[*Model parameters calibrated based on feedback from experimental output]

 Temperature profile and history can be utilized to interpret interfacial chemistry and phase composition



Temperature History

FY 19 ACCOMPLISHMENTS ON MG/STEEL INTERFACE -- PREDICTIVE FRAMEWORK FOR STRUCTURE-PROPERTY LINKAGE IN FSSW (PNNL)

Objective: Predict joint performance (Load-Displacement behavior)

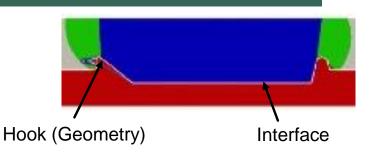
- Insights into understanding of features and mechanisms contributing to strength, ductility
- Identify desired space of "interfacial characteristics"

Joint Features:

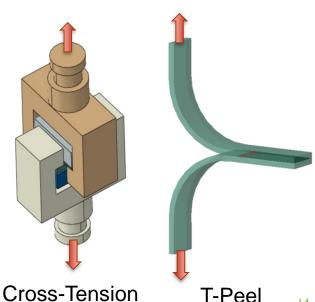
- Geometry (Hooking)
- Interface (Bonding)

Approach:

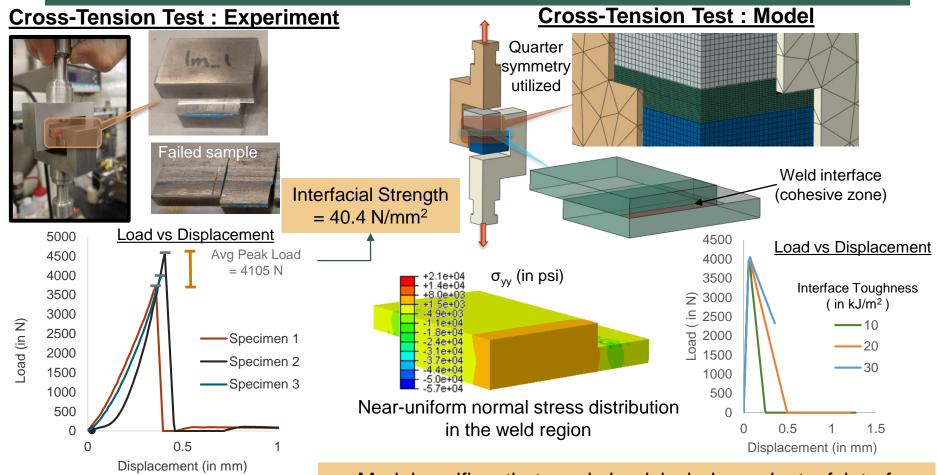
- Weld interface modeled as a cohesive zone
- Cohesive parameters, namely Strength and Toughness (Ductility), characterize the interface mechanically
- Use test geometries which have substantially different sensitivities to toughness and strength
- Advantage: Unique cohesive parameters, which can then be used to predict joint performance for other loadings and test geometries



FSSW Joint Morphology



FY19 ACCOMPLISHMENTS ON MG/STEEL INTERFACE -- CROSS-TENSION TEST TO CHARACTERIZE INTERFACIAL STRENGTH



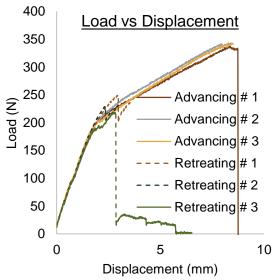
Preliminary data on Mg-Mg samples

Model verifies that peak load is independent of interface toughness

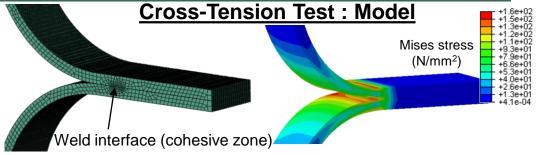
FY19 ACCOMPLISHMENTS ON MG/STEEL INTERFACE -- T-PEEL TEST TO CHARACTERIZE INTERFACE TOUGHNESS

T-Peel Test : Experiment



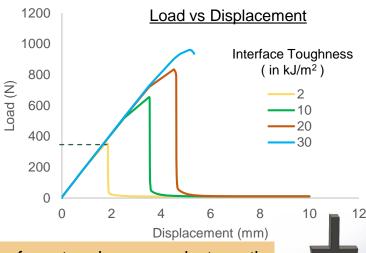


Preliminary data on Mg-Mg samples indicates difference in advancing vs retreating side



- Calibrated Interface Toughness* ~ 2 kJ/m2
- T-Peel: Peak load is a function of interface toughness

[*based on advancing side data]



- Calibrated values of interface toughness and strength will be validated with a third test geometry: U-Peel (experimental design underway)
- Cross-cutting: Similar testing procedure now being employed for CFRP-Steel adhesive bonding

RESPONSE TO PREVIOUS YEAR REVIEW COMMENTS - SELECTIVE

- This reviewer had trouble following the approach described as "Interface by Design." The reviewer said that this sounds interesting in principle, but the presentation provided no evidence to support that this "reverse of ICME" can be done simply from data analytics. The reviewer hoped to see more of the "cross-cutting foundational element" demonstrated next year.
 - We presented a successful demonstration in FY19 on how a structural Mg/Steel interface can be achieved with the "reverse ICME" interface-by-design process with ultrasonic welding.
- The reviewer said that, unfortunately, the project is pretty ill-conceived. Statements such as, there are no proven joining methods for dissimilar materials, is just unfounded (think mechanical fasteners and adhesives), and even for metallurgical bonding (welding methods) many approaches have been in production for decades. Also, according to the reviewer the notion that there is no understanding of the mechanics of bonding for dissimilar metal welds belies 50 years (or more) of literature on the subject. The reviewer understands the project is in the early stages, but an extensive literature review is clearly in order.
 - Our project intention was not understood properly by the Reviewer. Our perspective slide intends to focus on hard-to-weld material pairs, i.e., Mg/Steel, Al/Steel, Al/Mg, not general dissimilar metals combinations.
- The reviewer said that work has largely jumped to applications pre-selected based on PNNL/ORNL experience (the reviewer inquired where the industrial input is). The reviewer said that the focus is supposed to be defining the interfacial science first, but most of the results are essentially process models and do not address the interfacial science of these joints.
 - We used impact welding (OSU) to establish the forward mapping framework in FY19. Of course in picking the welding method to demonstrate the Interface-by-Design framework, we need to use the equipment available to the two labs.
- The reviewer said that collaborations are between two DOE national laboratories only, no other external collaborators to help "keep the peace." The reviewer pointed out that cooperative research and development agreements (CRADA) are in the plan ("will be pursued"), but the reviewer asked why not start it already. Generally speaking, interactions between DOE national laboratories tend to be minimal. The reviewer said that in this project, there was no overwhelming evidence to suggest that this is otherwise.
 - This is an early stage R&D project, and it is executed with strong interactions of ORNL/PNNL as evidenced in the presentation.

COLLABORATIONS AND TECHNOLOGY TRANSFER ACTIVITIES

Collaborations

- ORNL and PNNL: Modeling and experimental team
- ORNL and ANL on interface characterization of Mg/Mg and Mg/Steel

Technology Transfer

- Results will be disseminated through journal publications, conference presentations and discussions with industry
- Promising technologies will be further pursued through CRADAs with industry

Publications

- Huang, et al., Simulation of heat generation in magnesium alloy AZ31 ultrasonic welding by a validated thermal-mechanical model, revision submitted to *Journal of Materials Processing Technology*, 2019.
- Chen, et al., Ultrasonic Welding of AZ31B Magnesium Alloy: Interfacial Motion, Heat Generation and Weld Formation, *MRS Bulletin*, 2019.
- Gupta et al,. Mechanical characterization of the interface obtained in friction-stir-welded joints using cohesive zone modeling, TMS, 2019.
- Gupta et al., An integrated computational modeling approach to predict joint properties obtained in solid-state joining of dissimilar materials, World Congress on Computational Mechanics, 2018.

PROPOSED FUTURE WORK

- FSSW: Complete sensitivity analysis to provide recommendations back to process for optimal Mg-Steel FSSW interfacial characteristics to achieve desired strength and ductility
- UW: Further develop and demonstrate the Interface-by-Design framework with ultrasonic welding for other interfaces:
 - Mg/coated steel interfaces
 - Adhesively bonded interface
 - Other materials combinations
- Demonstrate the application of Interface-by-Design in novel welding/joining process discovery
- Demonstrate the advantage of Interface-by-Design in shortening joining process parameter development for enhanced bond strength

SUMMARY

Developed and demonstrated the forward and inverse Interface-by-Design framework on the Mg/Steel (bare) interface:

ORNL

- Developed and validated process modeling framework for ultrasonic welding process to predict interfacial temperature
- Developed and validated a multi-scale simulation framework for impact welding of Mg/Steel (bare) system to understand the bond formation mechanism at the interface
- Demonstrated the Interface-by-Design framework with ultrasonic welding on Mg/Steel (bare) system with model predicted process parameters and surface conditions

PNNL

- Validated process-structure model for friction stir scribe welding to predict interfacial morphology and temperatures
- Developed predictive framework for structure-property linkage in friction stir scribe welding
- Developed a combined modeling and experimental approach to have systematic mechanical characterization of interfaces across different joining techniques